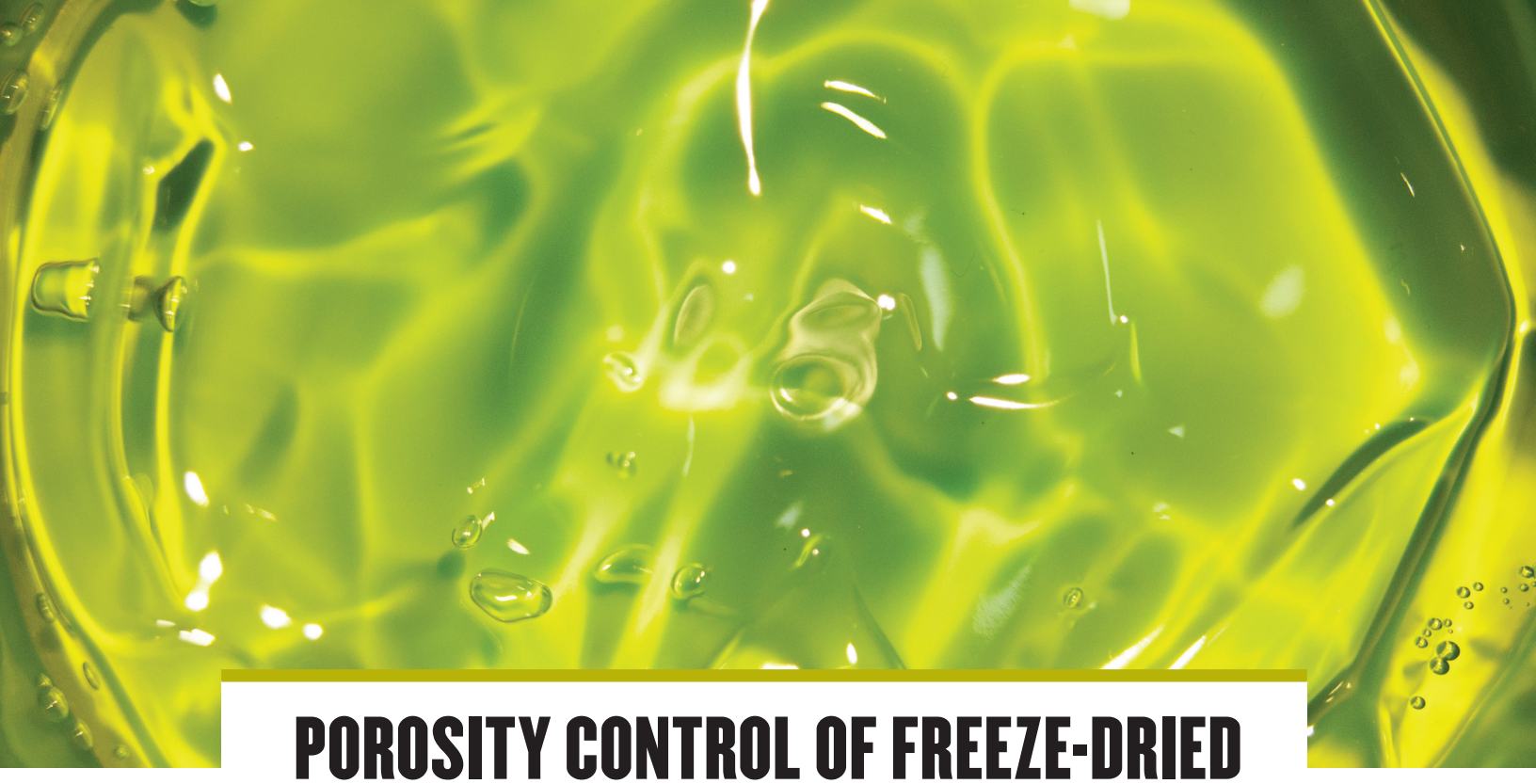

POROSITY CONTROL OF FREEZE-DRIED POLYACRYLAMIDE ORGANOGELS:

Effects of Cryoprotectants and Eutectic Solvent Mixtures

Student Author

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Mentor

Jeffrey P. Youngblood began his collegiate studies at Louisiana State University, majoring in chemistry and physics. In 1996 Youngblood commenced his PhD studies at the University of Massachusetts–Amherst in the Department of Polymer Science and Engineering under the direction of Professor Thomas McCarthy. He performed postdoctoral work at Cornell's Department of Materials Science and Engineering under Professor Christopher Ober. In 2003 Youngblood accepted a position in the School of Materials Engineering at Purdue University. Promoted to associate professor in 2009 and to professor in 2015, he uses his polymer expertise to investigate nanotechnology, surface science, advanced processing, and biomaterials.

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Abstract

Organic hydrogels are composed of an organic liquid phase in a three-dimensional network through polymerization. Hydrogels have been widely used in various applications, such as super insulators, smart drug delivery systems, and even biosensors. However, controlling hydrogel properties has continued to be a challenge in the materials engineering world. In theory, the combination of adding the cryoprotectants and eutectic solvents and then freeze-drying the hydrogels would result in the perfect gel. Freeze-drying organic hydrogels could result in an unusual combination of properties, including low density, low thermal conductivity, high surface area, and high porosity. The objective was to determine a mixture of cryoprotectants and/or eutectic liquids to form smaller pores in freeze-dried organogels, while maintaining a stable structure. The gels were synthesized with acrylamide (Am), methylenebisacrylamide (MBA), and ammonium persulfate (APS). Complete polymerization occurred within 24 hours, and samples were solvent exchanged with cryoprotectants/eutectics. Of all the solutions tested, a low concentration of 5w/v % ammonium carbonate (AC) resulted in a smaller pore size of approximately 30 µm. Minimizing the pore size increases the porosity within the foam, thus allowing the material to develop its remarkable properties of low density and high porosity. There are a wide range of possibilities for fully increasing the porosity, thus improving its properties. With further investigation of different cryoprotectants/eutectic mixtures, it was determined that the architecture of organic hydrogels can eventually be easily controlled and modified based on the intended application.

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Keywords

organogels, hydrogels, cryoprotectants, eutectic solvents, lypholization, porosity, acrylamide, methylenebisacrylamide, ammonium carbonate, polyvinylpyrrolidone

Aerogels are porous ultralightweight solid materials that have been prepared through the supercritical drying process. This method replaces the liquid component of a gel with air while the pore structure of the solid component remains intact. Aerogels are known for their remarkable materials properties of low density (0.001–0.5 g/cm^3), low thermal conductivity, high porosity (95% air), and high specific surface area (600–1000m^2/g) (Silica Aerogel, 2008). With these properties, applications of aerogels can range from superinsulators and supercapacitors to ultralight sensors and armor, as well as catalyst supports and drug release (Zheng, Javadi, Sabo, Cai, & Gong, 2013).

Aerogels can be fabricated from several different materials; however, the most common is an inorganic silica aerogel. Generally, silica aerogels are synthesized through the reaction mechanism of hydrolysis and condensation using tetramethoxysilane (TMOS) or tetraethoxysilane (TEOS), ethanol or methanol, water, and a catalyst. Once silica nanoparticles have formed from the liquid solution, the nanoparticles agglomerate, resulting in a silica gel formation (Błaszczyński, Ślosarczyk, & Morawski, 2013).

An organic aerogel follows a similar reaction; however, the solution is primarily composed of a monomer, cross-linker, initiator, and occasionally a catalyst. As shown in Figure 1, the gel formation mechanism occurs through annealing or ambient conditions over a period of time. As monomer particles form clusters, the particles subsequently cross-link, forming a solid gel. The network structure of an organic aerogel varies based on the composition and the polymerization process. The structure of a wet gel can be strengthened through an aging and soaking process in a solution. Generally, organic aerogels are less friable and can withstand a higher compressive strength than can inorganic aerogels (Pekala & Kong, 1989).

As mentioned, aerogels are fabricated through supercritical drying; however, an alternative method is lypholization, also known as freeze-drying. During this process, wet gels are frozen and solid pores are sublimated in a vacuum. Improper sublimation can result in shrinking or cracking in the solid structure from capillary pressures (Błaszczyński et al., 2013). Aging is known to strengthen and stabilize the gel network, as well as reduce pore size distribution (Pekala & Kong, 1989).

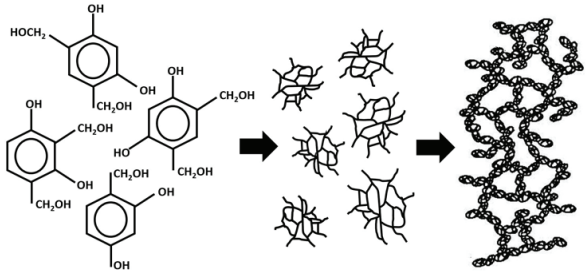

Figure 1. Gelation mechanism of RF monomers. (Redrawn with permission from Pekala, R. W., & Kong, F. M. (1989). A Synthetic Route to Organic Aerogels—Mechanism, Structure, and Properties. *Le Journal de Physique Colloques C4, 24*, 33–40.)

Organic liquids have a eutectic system that solidifies a mixture of components at a single eutectic temperature (Lee, Kim, Kim, & Lee, 2009). Studies show that eutectics reduce the microstructure size within a gel upon solidification (Lee et al, 2009). Cryoprotectants are used to preserve organisms from damage caused by ice formation, which is beneficial to organic aerogels (Lee et al., 2009). During lypholization, the use of cryoprotectants will inhibit ice nucleation and growth within the wet gel. A composition of both solvents will result in minimization of microstructure and ice formation of the organogel.

Organic hydrogels have been widely used in various applications, such as super insulators, smart drug delivery systems, and even biosensors. However, controlling hydrogel properties has remained a challenge.In theory, the combination of adding the cryoprotectants and eutectic solvents and then freeze-drying the hydrogels would result in the perfect gel. Freeze-drying organic hydrogels could result in an unusual combination of properties, including low density, low thermal conductivity, high surface area, and high porosity. The purpose of this study was to prepare an acrylamide (Am) gel with a reduced microstructure size using cryoprotectants and/or eutectic mixtures through the freeze-drying method.

EXPERIMENTAL

Materials

Acrylamide (Am), N,N-Methylenebis(acrylamide) (MBA, 98%), ammonium persulfate (APS), polyvinylpyrrolidone (PVP), ammonium carbonate (AC), ethylene glycol (EG), ethanol (EtOH), methanol (MtOH), dimethyl sulfoxide (DMSO), citric acid (CA), polyethylene glycol (PEG), and polyvinylalcohol (PVA) were all purchased from Sigma-Aldrich. All chemicals were of laboratory grade and used without purification.

Preparation of Acrylamide Organogels

Am wet gels were prepared following the procedure developed by the Ozmen group with modifications (Ozmen, Dinu, & Okay, 2007). For the initiator, a 20w/v % stock solution of APS was prepared with deionized (DI) water in vials. Fresh solution was prepared daily for effective polymerization of gels. Liquid solutions were prepared in vials for a total volume of 5 ml with composition of 5.8 wt % Am (monomer), 0.2 wt % MBA (cross-linker), and 2v/v % of APS aqueous solution. For a homogenous solution, a vial each of monomer and cross-linker were dissolved in DI water. The solution was stirred vigorously for 15 minutes, or until solids were completely dissolved. Subsequently, the initiator was added, vortexed, and placed into a cold sand bath. The temperature was slowly raised to 80° C; gelation occurred in approximately 2 hours. For complete polymerization, the gels remained at ambient temperature for 24 hours.

Solvent Exchange

Various solutions of cryoprotectants and eutectic mixtures were prepared for solvent exchange. As shown in Table 1, aqueous solutions were prepared at different concentrations. Am gels were washed with the solutions six times and soaked over a 72-hour period under ambient temperature. Following the soaking and solvent exchange process, gels were patted dry to remove any excess solution on the surface.

Freeze-Drying Process

The soaked gels were submerged into liquid nitrogen to control the quench rate. Subsequently, gels were immediately transferred to a freezer until all samples were ready for lypholization. The samples were vacuumed, then freeze-dried at –88° C for 2 to 5 days, depending on the preparation of the gel.

RESULTS AND DISCUSSION

Determining the composition of an organic wet gel was an extensive process. The initial gel was polymerized using the monomer, hydroxyethyl methyl methacrylate (HEMA), with a high water

Cryoprotectant/Eutectic	Solution
PVP	5, 7.5, 10wt %
AC	5, 7.5, 10wt %
PVP & AC	5, 7.5, 10wt %
CA	5, 7.5, 10wt %
PEG	10, 20, 30v/v %
EtOH	1, 3, 5v/v %
MtOH	1, 3, 5v/v %
PVA	1, 3, 5v/v %
DMSO	1, 3, 5v/v %

Table 1. Aqueous solutions of cryoprotectants and/or eutectic solvents at varying concentrations for solvent exchange (data from Lee et al., 2009).

concentration in the range of 70 to 85v/v %. However, HEMA is a hydrophobic monomer; therefore, it is not soluble in water and resulted in heterogeneous solution. The nonhomogeneous solution resulted in an opaque gel with a sponge texture. This may be due to the precipitation of polymers out of the monomer solution during polymerization (Refojo & Yasuda, 1965). According to Refojo, polymerization of HEMA gel in an aqueous solution of ethylene glycol (EG) yields a transparent gel (Refojo & Yasuda, 1965). HEMA gels of 10v/v % were prepared with aqueous solutions ranging from 50 to 80v/v % of EG-water. As shown in Figure 2, EG is miscible in both water and monomer at 70v/v %, whereas the solution polymerizes to a translucent gel at 50v/v % solution. Homogeneity for a sol-gel chemistry is essential in synthesizing aerogels, and this was achieved through an EG solvent system. However, the high concentrations of EG would be difficult to remove in the lyophilizer. For this reason, HEMA gels were no longer an option for further analysis in the production of aerogels.

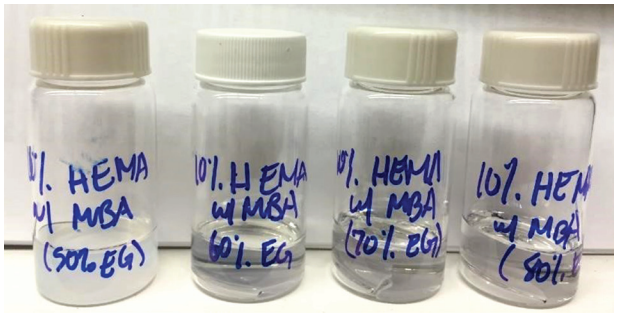

Figure 2. 10w/v % HEMA wet gels with 50, 60, 70, and 80v/v % of EG-water solution.

Preparation of the Am gel resulted in a homogenous solution with a transparent gel. Originally, gels were synthesized using a tetramethylethylenediamine (TEMED) catalyst and soaked in solutions (see Table 1) for 72 hours. All freeze-dried samples produced white monolithic foams. However, when the samples were cross-sectioned for microstructural analysis, hollow centers were discovered in all gels, as shown in Figure 3(a). The samples soaked in PVP solutions developed a large, thicker shell, whereas samples soaked in AC solutions produced a thickness of approximately 2 mm.

Air-filled hollowed foams could be the result of unsuitable ratios of the monomer and cross-linker within the gel. The use of a catalyst may have inhibited full polymerization of the gel as gelation occurred from the surface to the center. Hereafter, a catalyst was no longer added to the gel composition. To replace the effect of a catalyst, the samples were heat treated to approximately 80° C for 2 hours.

A penetrating cryoprotectant has the ability to move across cell membranes, whereas non-penetrating cryoprotectants do not. PVP was identified as a non-penetrating cryoprotectant; therefore, it was not expected to fill all pores within a gel. As a proposed solution, PVP aqueous solution was added into the

Figure 3. Preparation of 5.8wt % Am gels with different methods and solvent exchanged with various cryoprotectants/eutectics: (a) 5w/v % PVP with TEMED (soaked), (b) 10w/v% PVP no TEMED (in solution), (c) 1v/v % DMSO no TEMED (in solution).

monomer/cross-linker solution for polymerization. Following that, the gels were soaked in the PVP solution as well. As a result, solid foams were produced; however, phase separation was visible in the center of the foams, as shown in Figure 3(b). The center of the foam showed a crystallized structure, while the outer surface had a foam structure. This could have resulted from too high a concentration of PVP, so the gels were not fully polymerized. Using the same method of adding cryoprotectant into the solution, the 1% DMSO produced a solid monolithic foam, with no hollow center or phase separation. The results show that the structure of the foams are dependent on the compositions within a gel, as well as the solvent exchange/soaking process. If a catalyst is not required for polymerization, it should not be used so as to prevent hollow centers from forming in the freeze-dried foams. If a catalyst is required, a minimal amount should be added for complete gel formation. The monomer/cross-linker solution should be polymerized with the cryoprotectant/eutectic solution for full penetration, and lower concentrations of cryoprotectants/eutectic should be considered to avoid phase separation in the gels.

Several samples underwent slow freezing before lypholization, but there were no major differences in foam structure. Thus, samples continued to be flash frozen with liquid nitrogen. Samples soaked with CA, EtOH, MtOH, and EG solutions required an extensive amount of time to completely freeze-dry the gels into a foam structure. Therefore, these solutions were no longer considered due to time constraints this semester.

Microstructural Analysis

All freeze-dried gels displayed a stable network structure, as shown in Figures 4 and 5. Lyophilized organic gels are known to withhold a high compressive stress and are less friable, which is dependent on the structure of the foams. The pore size and structure of the foam depend on the composition of the gel and the concentrations used for cryoprotectants/eutectics. The freeze-dried samples show pore sizes of approximately 30 to 40 µm for 5w/v % AC and 50 µm for 7.5w/v % AC. In this case, a higher concentration of ammonium carbonate resulted in larger pores, whereas a lower concentration reduced the pore size. Overall, the pores in both concentrations were uniform in size. In the future, a lower concentration of AC could be used for the soaking process.

The microstructures shown in Figure 5 were more difficult to differentiate. Due to the reduction in pore

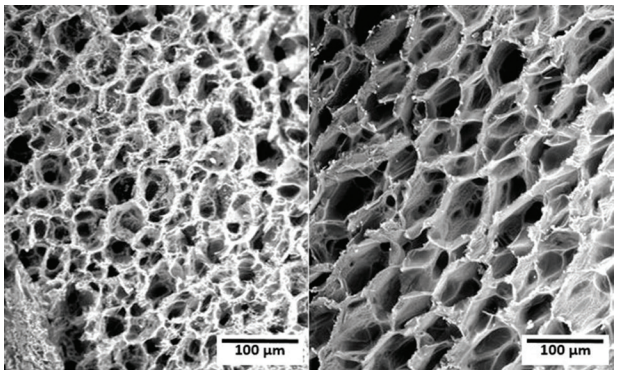

Figure 4. Freeze-dried samples of Am gels with 5w/v % AC (left) and 7.5w/v % AC (right).

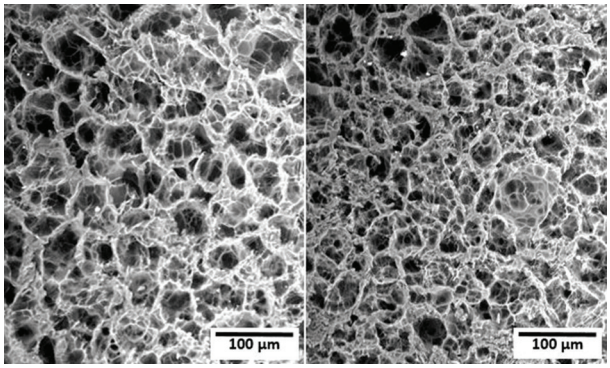

Figure 5. Freeze-dried samples of Am gels with 5w/v % PVP+AC (left) and 7.5w/v % PVP+AC (right).

size from the AC samples, a combination of PVP and AC were prepared for the solvent exchange process. In this case, the pores are not relatively uniform. The lower concentration of PVP+AC resulted in larger pore sizes, while the higher concentration resulted in relatively smaller pores. However, the differences in pore sizes are not major. The PVP was added to strengthen the structure in the foam and to prevent the cells from collapsing. The results show that a structurally stable membrane is a trade-off for pore size. This combined solution of PVP and AC can be analyzed further to determine the optimal composition for both a strong network structure and small pore size.

CONCLUSION

The synthesis of Am gels result in solid monolithic foams. The exclusion of a catalyst from the solution eliminated air-filled hollow centers from forming. The addition of cryoprotectant/eutectic solutions to the mixture to polymerize as one will result in a solid foam. However, to prevent phase separation

the concentrations of the solutions should not be overlooked. Of all the solutions tested, 5w/v % of AC was determined to have a great effect on pore size. A lower concentration of 1w/v % of AC may be used to determine if the previous results are correct. Although PVP and AC solutions stabilized the structure of the foams, there is a possibility that they will increase pore size as well. With future work, all samples can be analyzed further using Brunauer-Emmett-Teller (BET) surface analysis to determine which foams contain the highest surface area. Dynamic mechanical analysis (DMA) could be used to measure the mechanical properties of the foam, specifically the compressive strength. Additional testing could be performed on the foams with the cryoprotectants/eutectics listed in Table 1 using various concentrations.

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